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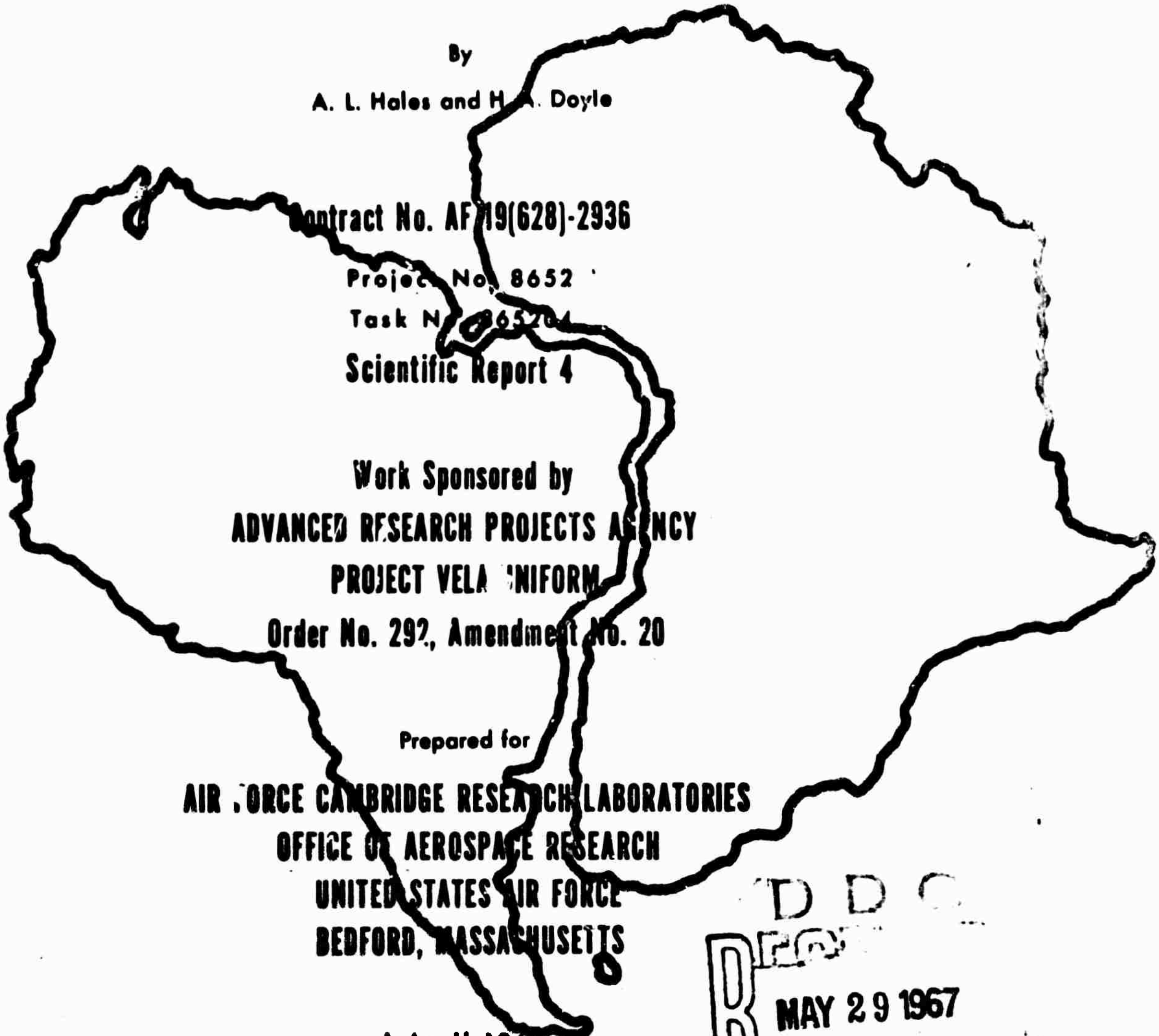
P AND S TRAVEL TIME ANOMALIES AND THEIR INTERPRETATION



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P and S Travel Time Anomalies and Their Interpretation

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Abstract. Study of the deviations of P and S travel times from the J-B tables at teleseismic distances has shown that there are regional differences in travel time. Both P and S are early in the central and eastern United States, late in the western United States. The differences have a range of about three seconds for P and eight seconds for S.

It can be deduced from the relation between the travel time residuals (1) that the change in shear velocity is approximately one and one-quarter times the change in P velocity, (2) that the observations imply a difference in Poisson's ratio between the two regions, and (3) that a model in which the shear modulus, μ, alone varies, the compressibility, k, remaining sensibly constant, fits the data best. It can be shown also that the differences between the P travel time residuals and the gravity anomalies in the central and western United States are not consistent with the Birch relation between velocity and density.

INTRODUCTION

One of the early results of the study of the deviations of observed P travel times from the Jeffreys-Bullen table times by Cleary and Hales (1963, 1965, 1966) was that there was a significant component of the deviations which was regionally dependent. Recently Doyle and Hales (1967) have studied the deviations of S travel times from the tables using the same method of analysis as Cleary and Hales. The S station residuals for North America ranged over eight seconds in contrast to the P residuals for which the range was only two to three seconds. The P and S residuals at the same station were correlated, the correlation coefficient being 0.75. Figure 1 shows a plot of the S residuals against the P residuals after adjustment to make the S residuals zero in the same region as the P residuals (see Doyle and Hales, 1967). A straight line fitted to the data using a method due to York (1966), had a slope of 3.72 ± 0.43. This line is shown in Figure 1. It is the purpose of this paper to explore the implications of the rather large ratio of the S residuals to those for P.

Residuals of this order of magnitude can only arise as a result of regional differences in the structure of the upper mantle. Let us compare portions of two upper mantle structures, one with P and S velocities, α_0 and β_0 respectively, and the other with velocities $\alpha_0 - \delta\alpha$, $\beta_0 - \delta\beta$, and assume

that the paths through the regions of difference each have length D. Then, to first order at least, the difference of the P travel times along the two paths, δt_P, will be $\frac{D\delta\alpha}{\alpha_0^2}$, whereas δt_S will be $\frac{D\delta\beta}{\beta_0^2}$. The ratio, $\delta t_S/\delta t_P$, is $\frac{\delta\beta}{\delta\alpha} \cdot \frac{\alpha_0^2}{\beta_0^2}$. In deriving the above results the effects of the differences in path geometry arising from possible differences in the ratios $\delta\alpha/\alpha_0$, and $\delta\beta/\beta_0$ have been neglected. In general the effects of changes in the path geometry will be small compared with the effects of changes in the velocities. We have, therefore,

$$\frac{\delta t_S}{\delta t_P} = \frac{\delta\beta}{\delta\alpha} \cdot \frac{\alpha_0^2}{\beta_0^2} = 3.72.$$

Assuming that $\frac{\alpha_0}{\beta_0} = \sqrt{3}$, corresponding to a Poisson's ratio of 0.25, we find $\delta\beta = 1.24\ \delta\alpha$.

If we assume that $\alpha_0 = 8.2$, $\beta_0 = 8.2/\sqrt{3} = 4.734$, it follows that $\alpha = 4.38 + 0.81\beta$. Figure 2 shows α, α/β and σ, Poisson's ratio, as functions of β for this model.* It should be noted that the relation between α and β given above applies only to those portions of the upper mantle in which the travel time differences arise.

MODEL CALCULATIONS

Many studies of the structure of the upper mantle have been carried out based upon the dispersion of surface waves. In fact general acceptance of the Gutenberg low

*Footnote: Similar conclusions to those of this paper follow for other values of β_0.

velocity layer in the upper mantle came from such studies. Many of these were studies of average structure over large areas, while others dealt specifically with local areas. Of these the two most relevant to the present discussion are those by Alexander (1963) of the western United States and McEvilly (1964) of the central United States.

We have calculated travel times at distances of 20 to 80 degrees for a number of upper mantle S velocity distributions based on surface wave and other studies.* In most of the cases the distributions have been adjusted to fit a Gutenberg S velocity structure at some depth depending on the range over which the original model was defined. The Gutenberg velocities used were those given by Press in the <u>Handbook of Physical Constants</u> (Press, 1966).

Table 1 lists the sources of the models, while Table 2 gives the velocity distributions. In calculating the travel times the Mohorovičić law, $v = v_1\left(\frac{r_1}{r}\right)^k$,

where $k = \dfrac{\log v_2 - \log v_1}{\log r_1 - \log r_2}$,

was used between the tabulated points. Figure 3 shows the differences in travel time of the models from those for the Gutenberg S velocity distribution over the distance range 25° to 85°. It will be noted that the differences decrease by about 20% from 30° to 80°. This is characteristic of the effects of P and S velocity changes in the upper mantle

*Footnote: The models were selected to show the effects of a wide range of upper mantle structures. They are not comprehensive. For example, travel times are not shown for Miss Lehmann's models. Teleseismic travel times for these models lie within the range shown in the figures.

and indicates that station anomalies should show a small decrease with distance. For the McEvilly Love wave model we have plotted as a dashed curve the difference of ScS travel time between the model and the Gutenberg distribution. This difference changes slowly from 95° to 25°. The station anomaly for ScS is always less than for S, ranging from 94% at 80° to 77% at 40° of the S station anomaly at the same distance.

The differences in travel time shown in Figure ? range over 14 seconds and are reasonably consistent with the range of the S station anomalies. It should be noted that McEvilly gave two S velocity distributions for the central United States, one based on Rayleigh wave dispersion, the other on Love wave dispersion. The differences between the times for the McEvilly Love wave model and Alexander's western United States model average 10 to 12 seconds, about 30% less than the maximum difference of 8 seconds in the observed S times (which are determined for one end of the path only). The difference between the times for the McEvilly Rayleigh wave model and Alexander's western U.S. model are positive and about one second. McEvilly ascribed the differences between the Rayleigh wave and Love wave models to anisotropy, i.e. to differences in velocity of SH and SV waves. For the travel time anomalies upon which this discussion is based, the upper mantle portion of the path was in most cases within 30° of the vertical, i.e. the major component of the particle motion was in the horizontal plane. It would be expected that the travel time anomalies would be consistent

with the Love wave model and not the Rayleigh wave model. Nevertheless, the discrepancies shown by the surface wave dispersion studies in the United States are puzzling and merit further investigation.

Figure 4 shows that changes of the velocity distribution in the upper mantle produce effects of different character from those resulting from changes in the lower mantle. Plotted in this figure are the differences of the travel times between the Gutenberg model and a number of other models, namely the McEvilly Love wave model, the Jeffreys model, the Anderson model and a model based on the Gutenberg IV model of MacDonald and Ness (1961) (in which the velocities in the lower mantle have been decreased). It will be noted that the differences for all models other than the Gutenberg IV model vary only one or two seconds over the teleseismic distance range, whereas those for the Gutenberg IV model increase systematically with distance. Comparison of this figure with the observed travel times of Doyle and Hales (1967) and Jeffreys (1966) supports the conclusion of Landisman, Satô and Nafe (1965) that changes of the S velocity distribution in the lower mantle such as were suggested by MacDonald and Ness are not permitted by the observations.

POISSON'S RATIO

It can be shown that the observed relation between the P and S residuals is not consistent with a constant

Poisson's ratio in those parts of the upper mantle for which the regional differences occur. If σ, given by $\frac{\alpha_2 - 2\beta^2}{2(\alpha^2 - \beta^2)}$, were constant, then α/β would be constant, $\delta\alpha/\alpha_0$ equal to $\delta\beta/\beta_0$, and the ratio of the residuals equal to α_0/β_0, i.e. 1.7 to 1.8. The 95% confidence limits for the slope of the regression line of S and P residuals are 2.86 and 4.58, and thus the possibility of constant σ is remote.

The only one of the elastic constants which can be determined independently of possible changes of density is σ. Expressed in terms of $\delta\alpha$

$$\sigma = \tfrac{1}{4}\left(1 - \frac{3.44\ \delta\alpha}{\alpha_0}\right) \quad \text{to the first order,}$$

assuming as before that $\alpha_0 = \sqrt{3}\beta_0$. In terms of δt_P, the P station residual

$$\sigma = \tfrac{1}{4}\left(1 - \frac{3.44\alpha_0}{D}\ \delta t_P\right) .$$

Figure 5 shows σ as a function of δt_P for δt_P ranging from 0 to 3 seconds, for α_0 = 8.2 km/sec and various values of D. It should be noted that the starting point for the calculation corresponds to a high velocity upper mantle, and thus to the early arrivals rather than to the zero P residual of Cleary-Hales (1966).

THE ELASTIC CONSTANTS AND DENSITY

If low shear velocities in the upper mantle are due to an approach to melting, perhaps only partial, then the

principal effect would be on the shear modulus μ. It was suggested (Hales, 1964) that in such cases $\delta\alpha/\alpha$ would lie between 2/3 and 4/9 of $\delta\beta/\beta$. The upper limit was derived from a model in which λ remained constant, and the lower from one in which k remained unchanged. These limits correspond to $\delta\beta/\delta\alpha$, lying between 0.87 and 1.30, whereas the observed value is 1.24, the 95% confidence limits being 0.96 and 1.53. Thus the model in which k is constant fits the observations reasonably well. No allowance has been made for the effect of possible changes of density.

The attenuation of seismic energy in the upper mantle was discussed by Anderson, Ben-Menahem and Archambeau (1965). They found that the attenuation of surface waves could be represented by a model in which the elastic constants were complex, the imaginary component of μ, μ^* being relatively large in the low velocity zone. They concluded that a model in which the imaginary part of the incompressibility $k^* = 0$, i.e. in which there were no losses in pure compression, seemed to be a good one, although experimental error permitted values of k^* as high as $\mu^*/2$. Thus the attenuation studies suggest also that the changes in μ are larger than those in the other elastic constants.

There is good evidence that there are density anomalies in the upper mantle to the west of the

Rocky Mountain front. Seismic refraction studies by the Crustal Structure Branch of the U. S. Geological Survey (Pakiser and Zietz, 1965) show that the continental crust in the western United States is generally thinner than 40 km, whereas in the central and eastern United States the crustal thickness is generally greater than 40 km. Although some structures such as the Sierra Nevadas are locally compensated, it is clear that a considerable part of the compensation for the elevated region to the west of the Rocky Mountain front comes from lower densities in the upper mantle.

The Bouguer gravity anomalies in the western plateau region are of order -200 milligals over large areas (Woollard and Joesting, 1964). It is not clear how much of these large negative anomalies should be ascribed to density variations in the upper mantle, but 200 milligals would appear to be an upper limit.

Supposing that the density anomaly is $\delta\rho$, extends over D' km depth range, and can be represented as an infinite plate, then $D'\delta\rho = 4.75$ and $\frac{D'\delta\rho}{\rho_0} = 1.4$ km. For arrivals at teleseismic distances, the rays in the upper mantle are inclined at angles of about 30° to the radius, so that $D' = 0.9\ D$ approximately and thus $D\delta\rho$ is 5.2. Since the range of S station anomaly $\frac{D\delta\beta}{\beta_0^{\,2}} = 8$ sec, $\frac{D\delta\beta}{\beta_0}$ is equal to 38 km. Since $\beta = \sqrt{\frac{\mu}{\rho}}$, it follows that $\delta\beta/\beta_0 = \frac{1}{2}\frac{\delta\mu}{\mu_0} - \frac{1}{2}\frac{\delta\rho}{\rho_0}$, and thus the contribution to $\delta\beta/\beta_0$ of the density change is about 1/24 of the contribution from $\delta\mu/\mu_0$. Furthermore it is of opposite sign.

The model of elastic constant change which best fits the observations is one in which μ alone changes and k remains constant. For this model the ratio of the S residual to the P residual is 3.9, whereas the observed value was 3.72. The 95% confidence limits of the observed value are 2.86 and 4.58. If we fit a model to the lower limit of 2.86, $\delta k/k_0$ is found to be $\delta\mu/4\mu_0$ approximately.

In summary then, the observed P and S travel time anomalies are consistent with a model in which μ alone changes, k remaining constant, but relative changes in k up to 25% of those in μ are allowed by the observational data. For a model in which λ remains constant the ratio of the S anomalies to the P anomalies is 2.60 and lies outside the 95% confidence limits for the observations.

Birch (1961) has given a relation between α and ρ for a wide range of rock types. From Birch's data it follows that $d\alpha/d\rho$ is about 3 km/sec per gm/cm^3 for most rocks. Since δt_P has a range of 2 seconds and is equal to $\frac{D\delta\alpha}{\alpha_0{}^2}$, it follows that $D\delta\alpha = 134.4$ km^2/sec. It has been shown that $D\delta\rho$ is of order 5.2. Thus $\frac{\delta\alpha}{\delta\rho} = 26$ and is an order of magnitude larger than the value expected if Birch's relation were applicable in this region of the upper mantle. The infinite plate calculation used above may not be appropriate. For reasonable three dimensional structures $D\delta\rho$ lies between 10 and 15 and $\frac{\delta\rho}{\delta\rho}$ between 13 and 9, considerably greater than value of about 3 expected of Birch's relation.

THE EFFECT OF TEMPERATURE

Experimental determinations of the effect of temperature on the velocity of shear waves in rocks at high pressure were given by Birch, Schairer and Spicer (1942, p. 83) and Birch (1963). For ultrabasic rocks the relative change in β is of order 0.004 to 0.008 per 100° C. Since the range of the S residuals is 8 seconds, $\frac{\delta\beta}{\beta_0}$ = 0.378, 0.189, 0.0756 and 0.038 for D = 100, 200, 500 and 1000 km respectively. Thus if the difference in temperature were spread over 1000 km depth range, the temperature difference required would be 500° to 1000° C.

However, Anderson, Ben-Menahem and Archambeau (1965) found low values of Q over a depth range of about 300 to 400 km, so that if the reduction in shear velocity and the low Q values are associated, as seems probable, the major part of the effect would occur over 300 to 400 km, and considerably greater temperature differences than 500° C would be required.

Soga, Schreiber and Anderson (1966) have estimated the seismic velocities at high temperatures from those at relatively low temperatures. For Mg_2SiO_4 $\partial\mu/\partial T$ is about 0.0060 per 100° C. Thus using the Soga *et al.* data the temperature changes required would be of order 600°C over 1000 km and 1250°C over 500 km.

The Soga *et al.* equations are

$\alpha = 7.750 - 0.000362T$ and

$\beta = 4.513 - 0.000271T$ to the first order for Mg_2SiO_4

where T is the temperature. From these equations it can be deduced that for changes of temperature $\frac{\delta\beta}{\delta\alpha} \cdot \frac{\alpha^2}{\beta^2}$ is 2.25,

which is significantly less than the observed value of $\delta t_S/\delta t_P$. It is therefore unlikely that the S wave station anomalies can be accounted for in terms of changes in temperature unless the temperatures are such that one component of the system approaches its melting point or some new thermoelastic effect occurs.

If one component of the system were to approach melting point, or if the intercrystalline constraints were relaxed in some other process, changes in shear velocity much greater than found by Birch and Bancroft (1938, 1940), Birch (1963) or Soga et al. (1966) might occur.

CORRELATION OF STATION RESIDUALS WITH HEAT FLOW

It was pointed out by Cleary and Hales (1966) that station anomalies were negative in shield areas and that these were, in general, regions of low heat flow. Recently published heat flow values by Hyndman (1967) for eastern Queensland average 1.2 μ cal/cm^2 sec, whereas those in southeastern Australia and Tasmania have a mean of 2.36 $\pm$ 0.38 μ cal/cm^2 sec (Howard and Sass, 1964). The P station anomalies in southeastern Australia and Tasmania are positive, whereas those for Brisbane and Charter's Towers in eastern Queensland are negative.

Thus there appears to be a correlation between positive station residuals and high heat flow. It is our opinion that the station anomalies originate largely in the upper

mantle, and so it would appear that the high heat flows are associated with higher temperatures in the upper mantle

CONCLUSION

The general conclusion to be drawn from this discussion of P and S travel time anomalies in the United States is that the differences between the central and western regions are due in the main to higher temperatures in the upper mantle of the western United States such that there is an approach of one constituent to melting with a consequent reduction of μ, or alternatively that the intercrystalline constraints are somehow reduced at high temperature.

There is no doubt that some parts of the travel time deviations arise from differences of crustal structure and differences of composition in the crust, but this study suggests strongly that the major part of the deviations for the two regions are to be ascribed to differences in temperature conditions in the upper mantle. The scatter in the ratio $\delta t_S/\delta t_P$ is probably due in some measure to the differences in crustal structure for which it is probable that $\frac{\delta\beta}{\beta_0{}^2} \cdot \frac{\alpha_0{}^2}{\delta\alpha}$ would be of order 1.7 to 1.8.

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Figure Captions

Figure 1. P and S station anomalies

Figure 2. α, α/β and σ as functions of β for a model in which $\alpha_0 = 8.2$ km/sec, $\beta_0 = \alpha_0/\sqrt{3}$.

Figure 3. Differences between the calculated travel times for various models and those for the Gutenberg velocity distribution (Model 0). The dashed curve gives differences between calculated ScS travel times for the McEvilly Love wave model and those for Model 0.

Figure 4. Differences between calculated travel times for several models and the Model 0.

Figure 5. σ as a function of δt_P for δt_P ranging from 0 to 3 sec, for $\alpha_0 = 8.2$ km/sec and various values of D.

Table Captions

Table 1. Sources of models.

Table 2. Velocity distributions for the models. The bars indicate discontinuities.

TABLE 1. SOURCES OF MODELS

Model No.	
0	Gutenberg: from the table in Handbook of Physical Constants (1966) compiled by F. Press. Standard crust added. Times for this model were used as bases for Figures 3 and 4.
9	Jeffreys: from the table in Handbook of Physical Constants (1966), compiled by F. Press. Crust with velocity 3.6 km/sec added.
4 5 6 8 10	Models 4, 5, 6, 8 and 10 have Gutenberg lower mantle, and increased velocities in the upper mantle as compared with model 0.
1	Anderson model (Physics and Chemistry of the Earth, 6, p. 116, 1965) fitted to Gutenberg lower mantle at 1400 km.
2	McEvilly (1964) Rayleigh model fitted to Gutenberg lower mantle at 500 km.
11	McEvilly (1964) Love model fitted to Gutenberg lower mantle at 500 km.
3	Alexander (1963) crust and upper mantle fitted to Gutenberg lower mantle at 500 km.
7	Brune and Dorman (1963) Canadian Shield model plotted to Gutenberg lower mantle at 500 km.
12	MacDonald and Ness (1961) Gutenberg IV model. Note that this model consists of layers of constant velocity. As a result the differences from the Gutenberg Handbook model are irregular.

TABLE 2, Part 2.

Model 2		Model 3		Model 7		Model 11		Model 1		Model 9		Model 12	
Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)
6371.2	3.50	6371.2	3.60	6371.2	3.47	6371.2	3.50	6371.2	3.600	6371.2	3.600	6371.2	3.55
6360.2	3.50	6345.2	3.60	6365.2	3.47	6360.2	3.50	6345.2	3.600			6350.0	3.55
6360.2	3.68	6345.2	4.10	6365.2	3.64	6360.2	3.68	6345.2	3.900			6350.0	3.80
6351.2	3.68	6321.2	4.10	6354.7	3.64	6351.2	3.68	6335.2	3.900	6338.0	3.600	6340.0	3.80
6351.2	3.67			6354.7	3.85	6351.2	3.94	6335.2	4.600	6338.0	4.353	6340.0	4.65
6333.2	3.67			6336.0	3.85	6333.2	3.94	6321.2	4.620			6320.0	4.65
6333.2	4.67	6321.2	4.60	6336.0	4.72	6333.2	4.75					6320.0	4.60
6309.2	4.67	6306.2	4.65	6256.0	4.72	6309.2	4.75	6301.2	4.440			6310.0	4.60
6309.2	4.47	6246.2	4.40	6256.0	4.54	6309.2	4.83	6281.2	4.339			6310.0	4.57
6269.2	4.47	6235.2	4.35			6269.2	4.83	6261.2	4.340	6275.2	4.444	6300.0	4.57
6269.2	4.45					6269.2	4.80	6241.2	4.340			6300.0	4.51
		6210.2	4.36					6221.2	4.340	6211.2	4.539	6290.0	4.51
				6156.0	4.54			6201.2	4.500			6290.0	4.46
		6171.2	4.40	6156.0	4.51			6181.2	4.500	6148.2	4.638	6280.0	4.46
6089.2	4.45			6056.0	4.51	6089.2	4.80	6161.2	4.500			6280.0	4.41
6045.2	4.66	6071.2	4.60	6056.0	4.76	6045.2	4.85	6141.2	4.500	6084.2	4.741	6270.0	4.41
5995.2	4.82			5976.0	4.76	5995.2	4.90	6121.2	4.500	6021.2	4.850	6270.0	4.37
5945.2	5.00	5971.2	4.95	5945.2	5.00	5945.2	5.00	6101.2	4.500	5958.2	4.962	6250.0	4.37
								6081.2	4.500			6250.0	4.35
5871.2	5.30	5871.2	5.30	5871.2	5.30	5871.2	5.30	6061.2	4.500	5894.2	5.227	6220.0	4.35
								6041.2	4.500			6220.0	4.36
5771.2	5.60	5771.2	5.60	5771.2	5.60	5771.2	5.60	6021.2	4.500	5831.2	5.463	6200.0	4.36
								5991.2	4.800			6200.0	4.38
5671.2	5.90	5671.2	5.90	5671.2	5.90	5671.2	5.90	5946.2	5.040	5768.2	5.670	6170.0	4.38
								5916.2	5.400			6170.0	4.42
5571.2	6.15	5571.2	6.15	5571.2	6.15	5571.2	6.15	5841.2	5.400	5704.2	5.850	6150.0	4.42
								5721.2	5.400			6150.0	4.46
5471.2	6.30	5471.2	6.30	5471.2	6.30	5471.2	6.30	5621.2	6.200	5577.2	6.002	6120.0	4.46
								5521.2	6.230	5451.2	6.295	6120.0	4.52
5371.2	6.35	5371.2	6.35	5371.2	6.35	5371.2	6.35	5421.2	6.322	5324.2	6.395	6070.0	4.52
								5271.2	6.421	5224.2	6.483	6070.0	4.66
5171.2	6.50	5171.2	6.50	5171.2	6.50	5171.2	6.50	5071.2	6.550	5070.2	6.564	6020.0	4.66
												6020.0	4.82
4971.2	6.60	4971.2	6.60	4971.2	6.60	4971.2	6.60	4971.2	6.600	4944.2	6.637	5970.0	4.82
										4817.2	6.706	5970.0	5.00
4771.2	6.75	4771.2	6.75	4771.2	6.75	4771.2	6.75	4771.2	6.750	4690.2	6.770	5920.0	5.00
												5920.0	5.14
4571.2	6.85	4571.2	6.85	4571.2	6.85	4571.2	6.85	4571.2	6.850	4563.2	6.833	5870.0	5.14
												5870.0	5.38
4371.2	6.95	4371.2	6.95	4371.2	6.95	4371.2	6.95	4371.2	6.950	4437.2	6.893	5720.0	5.38
										4310.2	6.953	5720.0	5.69
4171.2	7.00	4171.2	7.00	4171.2	7.00	4171.2	7.00	4171.2	7.000	4183.2	7.012	5670.0	5.69
												5670.0	5.96
3971.2	7.10	3971.2	7.10	3971.2	7.10	3971.2	7.10	3971.2	7.100	4056.2	7.074	5570.0	5.96
										3930.2	7.137	5570.0	6.15
3771.2	7.20	3771.2	7.20	3771.2	7.20	3771.2	7.20	3771.2	7.200	3803.2	7.199	5470.0	6.15
										3676.2	7.258	5470.0	6.24
3571.2	7.25	3571.2	7.25	3571.2	7.25	3571.2	7.25	3571.2	7.250	3549.2	7.314	5370.0	6.24
												5370.0	6.34
3471.2	7.20	3471.2	7.20	3471.2	7.20	3471.2	7.20	3471.2	7.200	3486.2	7.304	5170.0	6.34
												5170.0	6.47
3451.2	7.20	3451.2	7.20	3451.2	7.20	3451.2	7.20	3451.2	7.200	3473.2	7.304	4970.0	6.47
												4970.0	6.61
												4770.0	6.61
												4770.0	6.72
												4570.0	6.72
												4570.0	6.81
												4370.0	6.81
												4370.0	6.88
												4170.0	6.88
												4170.0	6.94
												3970.0	6.94
												3970.0	7.06
												3770.0	7.06
												3770.0	7.14
												3570.0	7.14
												3570.0	7.11
												3470.0	7.11

TABLE 2, Part 1.

Model 0		Model 4		Model 5		Model 6		Model 8		Model 10	
Radius (km)	Velocity (km/sec)	Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)	Radius (km)	Vel. (km/s)
6371.2	3.60	6371.2	3.60	6371.2	3.60	6371.2	3.60	6371.2	3.60	6371.2	3.60
6345.2	3.60	6345.2	3.60	6345.2	3.30	6345.2	3.60	6345.2	3.60	6345.2	3.60
6345.2	3.90	6345.2	3.90	6345.2	3.90	6345.2	3.90	6345.2	3.90	6345.2	3.90
6335.2	3.90	6335.3	3.90	6335.2	3.90	6335.2	3.90	6335.2	3.90	6335.2	3.90
6335.2	4.60	6335.2	4.75	6335.2	4.75	6335.2	4.75	6335.2	4.75	6335.2	4.75
		6321.2	4.80								
6311.2	4.60	6306.2	4.65	6296 2	4.80						
						6271.2	4.80	6271.2	4.80		
6271.2	4.40	6246.2	4.40	6246.2	4.40	6246.2	4.40	6246.2	4.60	6271.2	4.80
		6235.2	4.35	6235.2	4.35	6235.2	4.35	6235.2	4.55		
6221.2	4.35	6210.2	4.36	6210.2	4.36	6210.2	4.36	6210.2	4.50	6221.2	4.75
								6160.2	4.48		
6171.2	4.40	6171.2	4.40	6171.2	4.40	6171.2	4.40			6171.2	4.70
								6095.2	4.52		
6071.2	4.60	6071.2	4.60	6071.2	4.60	6071.2	4.60	6071.2	4.60	6071.2	4.75
										6021.2	4.80
5971.2	4.95	5971.2	4.95	5971.2	4.95	5971.2	4.95	5971.2	4.95	5945.2	5.00
5871.2	5.30	5871.2	5.30	5871.2	5.30	5871.2	5.30	5871.2	5.30	5871.2	5.30
5771.2	5.60	5771.2	5.60	5771.2	5.60	5771.2	5.60	5771.2	5.60	5771.2	5.60
5671.2	5.90	5671.2	5.90	5671.2	5.90	5671.2	5.90	5671.2	5.90	5671.2	5.90
5571.2	6.15	5571.2	6.15	5571.2	6.15	5571.2	6.15	5571.2	6.15	5571.2	6.15
5471.2	6.30	5471.2	6.30	5471.2	6.30	5471.2	6.30	5471.2	6.30	5471.2	6.30
5371.2	6.35	5371.2	6.35	5371.2	6.35	5371.2	6.35	5371.2	6.35	5371.2	6.35
5171.2	6.50	5171.2	6.50	5171.2	6.50	5171.2	6.50	5171.2	6.50	5171.2	6.50
4971.2	6.60	4971.2	6160	4971.2	6.60	4971.2	6.60	4971.2	6.60	4971.2	6.60
4771.2	6.75	4771.2	6.75	4771.2	6.75	4771.2	6.75	4771.2	6.75	4771.2	6.75
4571.2	6.85	4571.2	6.85	4571.2	6.85	4571.2	6.85	4571.2	6.85	4571.2	6.85
4371.2	6.95	4371.2	6.95	4371.2	6.95	4371.2	6.95	4371.2	6.95	4371.2	6.95
4171.2	7.00	4171.2	7.00	4171.2	7.00	4171.2	7.00	4171.2	7.00	4171.2	7.00
3971.2	7.10	3971.2	7.10	3971.2	7.10	3971.2	7.10	3971.2	7.10	3971.2	7.10
3771.2	7.20	3771.2	7.20	3771.2	7.20	3771.2	7.20	3771.2	7.20	3771.2	7.20
3571.2	7.25	3571.2	7.25	3571.2	7.25	3571.2	7.25	3571.2	7.25	3571.2	7.25
3471.2	7.20	3471.2	7.20	3471.2	7.20	3471.2	7.20	3471.2	7.20	3471.2	7.20
3451.2	7.20	3451.2	7.20	3451.2	7.20	3451.2	7.20	3451.2	7.20	3451.2	7.20

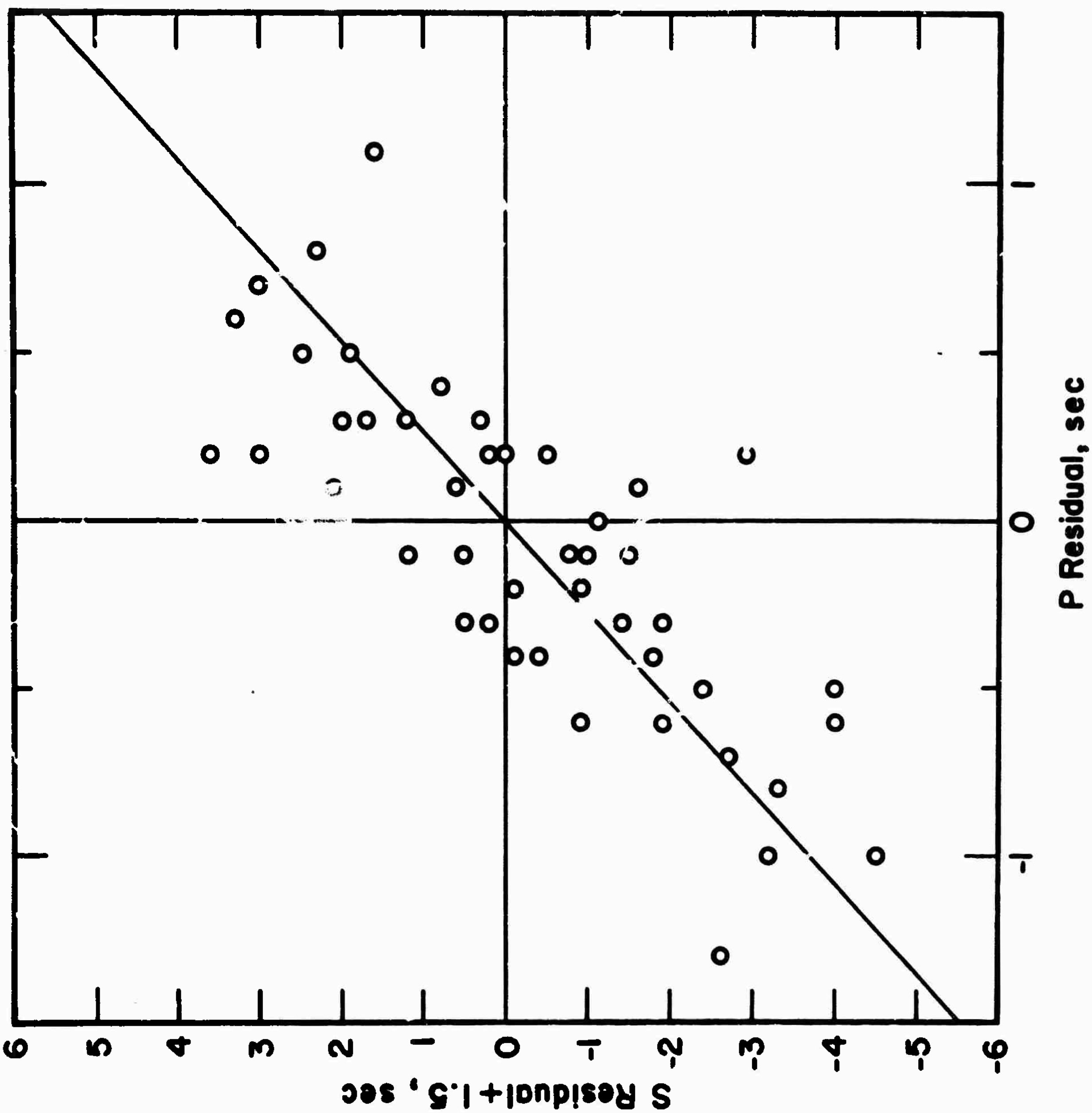


Figure 1

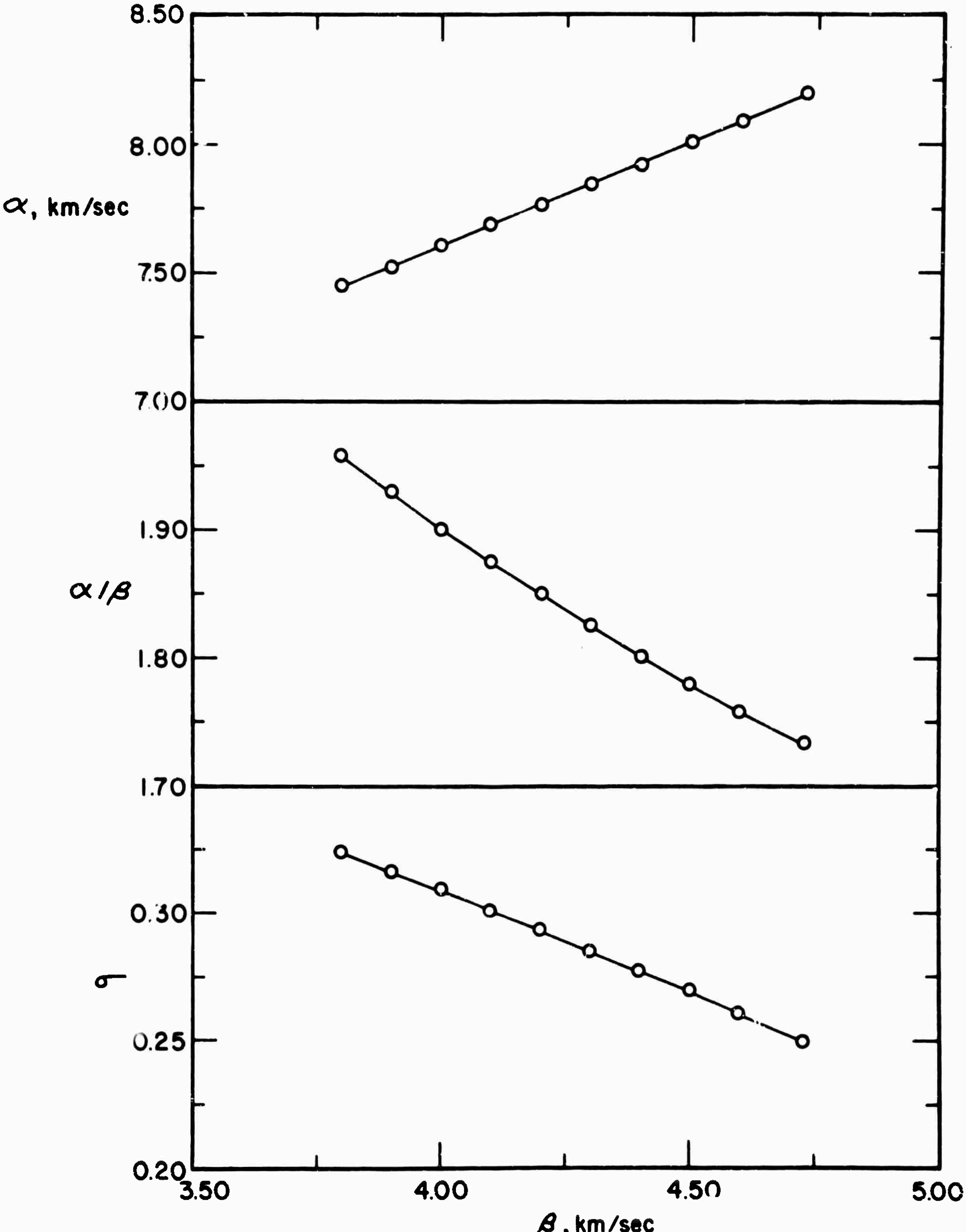

8.50
8.00
α, km/sec
7.50
7.00
1.90
α/β
1.80
1.70
0.30
σ
0.25
0.20
3.50
4.00
4.50
5.00
β, km/sec

Figure 2

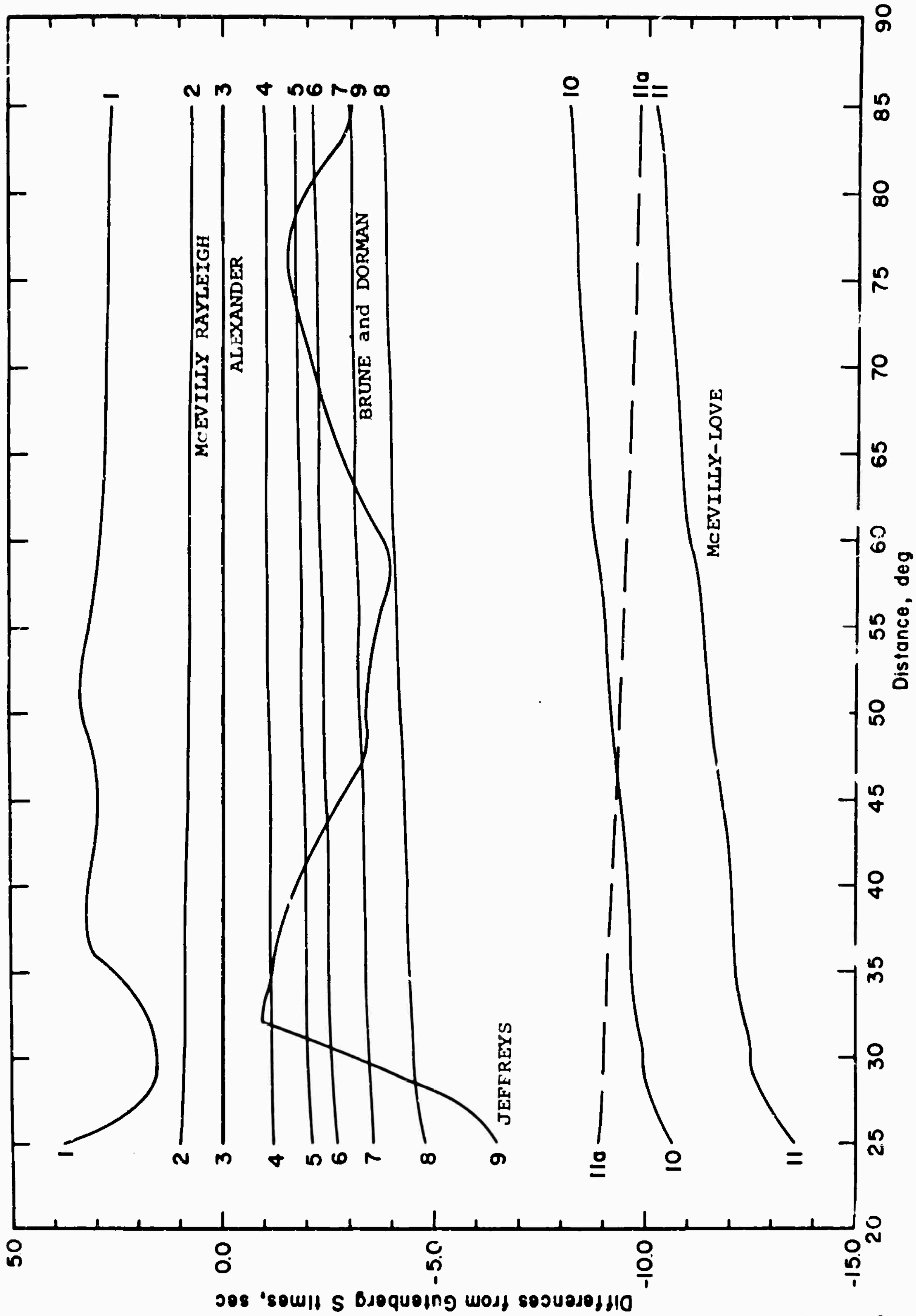

McEVILLY RAYLEIGH
ALEXANDER
BRUNE and DORMAN
JEFFREYS
McEVILLY-LOVE
Distance, deg
Differences from Gutenberg S times, sec
1
2
3
4
5
6
7
8
9
10
11
11a

Figure 3

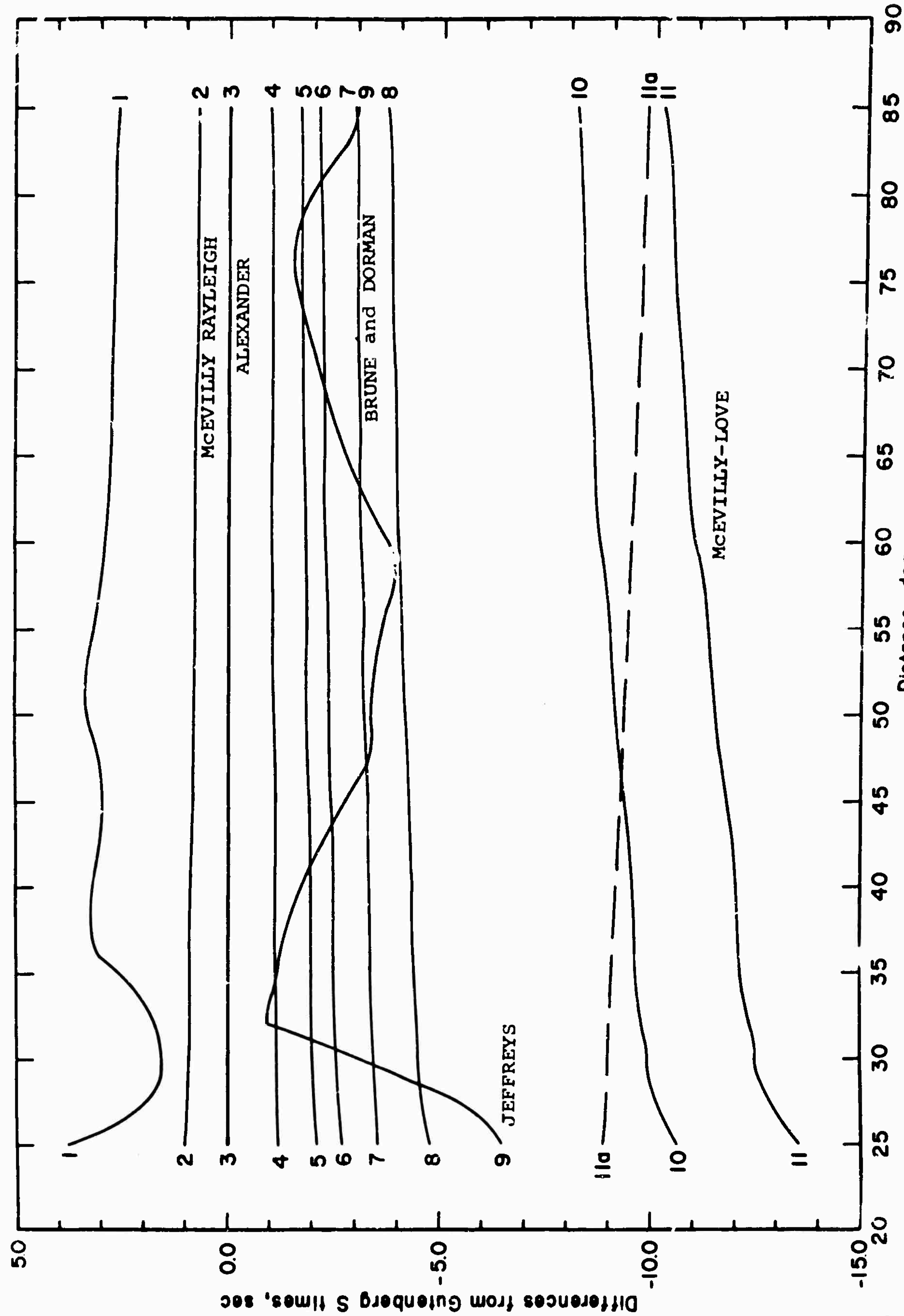

Differences from Gutenberg S times, sec
Distance, deg
McEVILLY RAYLEIGH
ALEXANDER
BRUNE and DORMAN
JEFFREYS
McEVILLY-LOVE
5.0
0.0
-5.0
-10.0
-15.0
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
1
2
3
4
5
6
7
8
9
10
11
11a

Figure 3

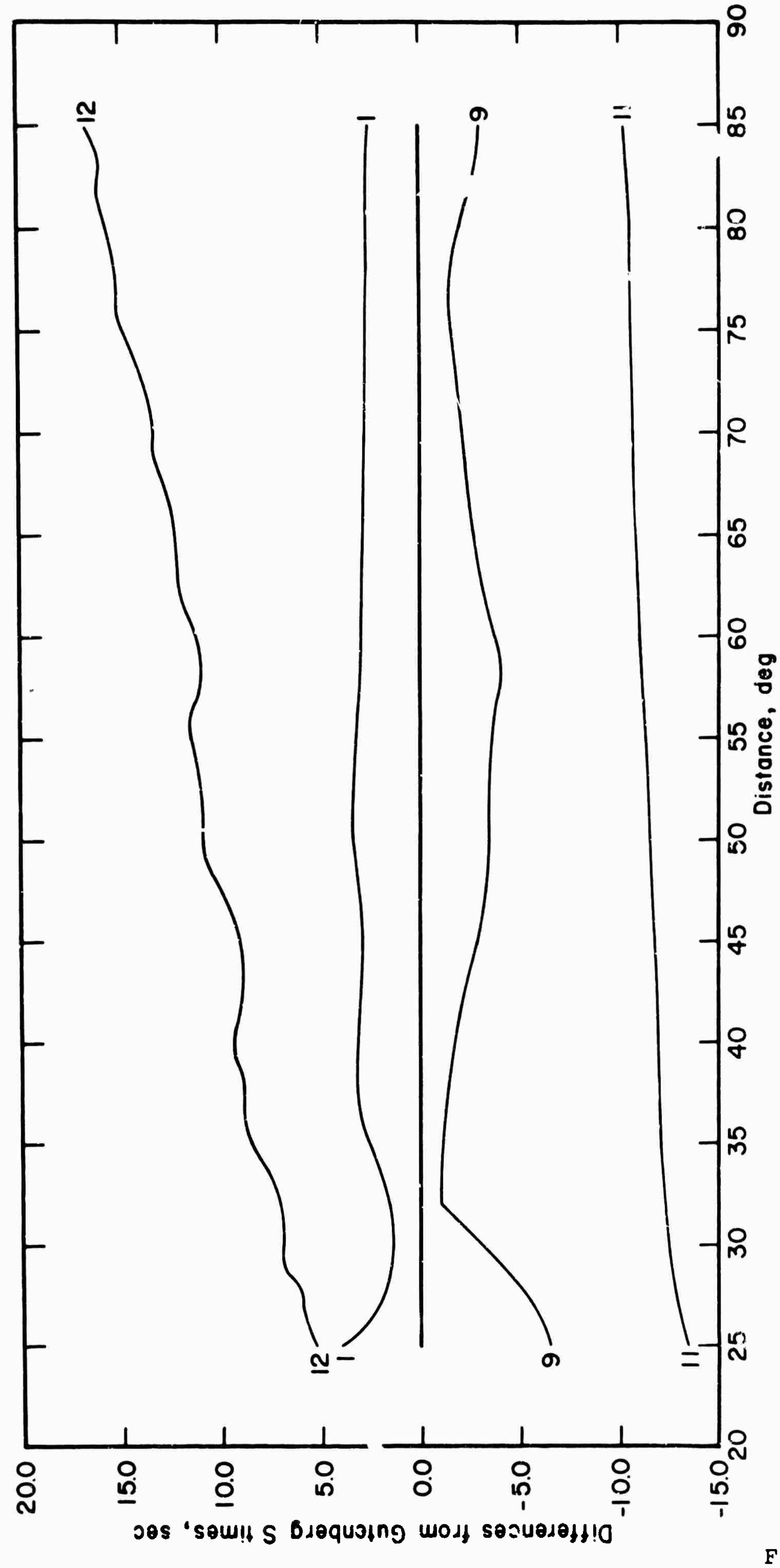
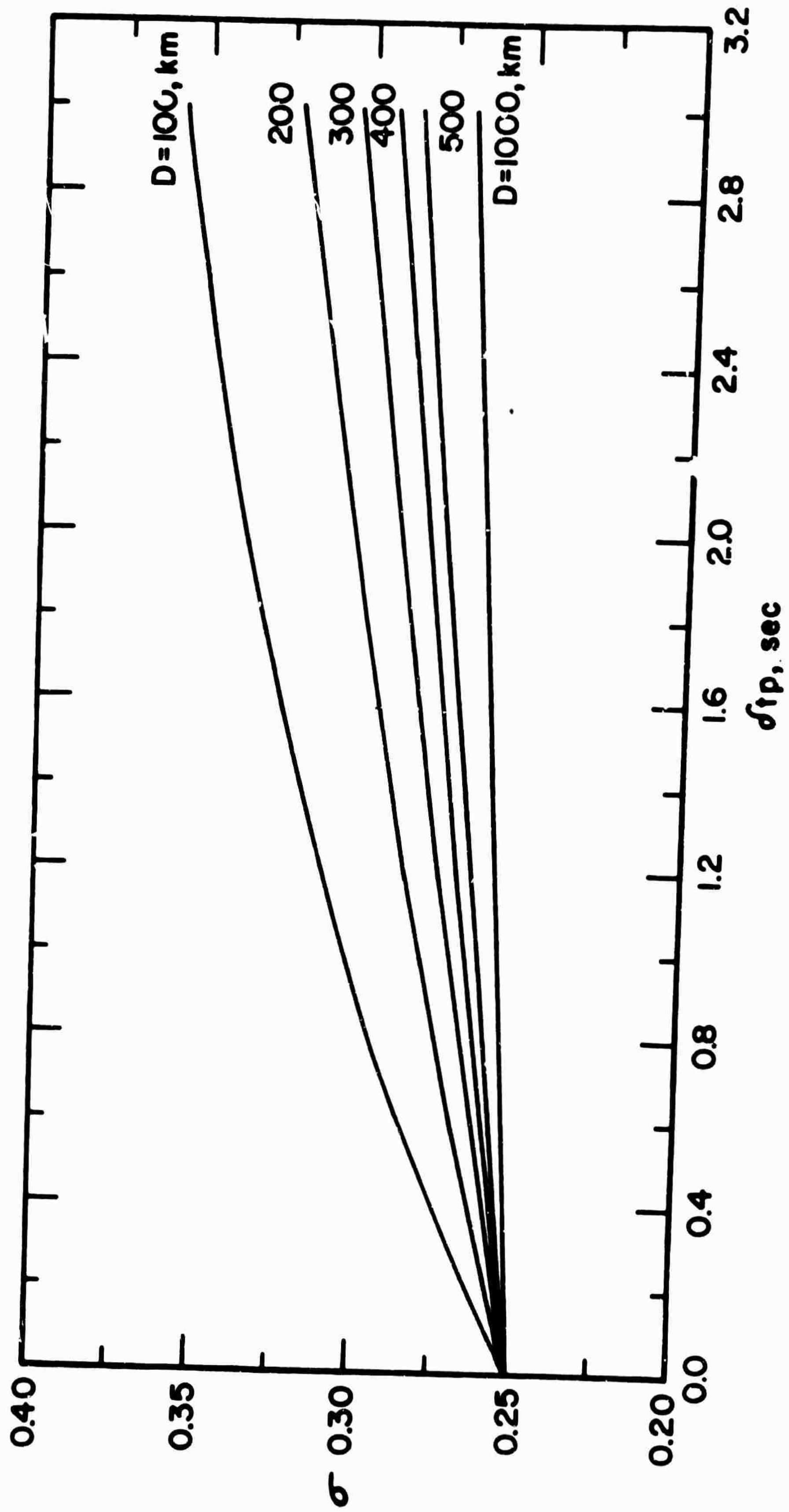

Distance, deg
Differences from Gutenberg S times, sec
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
12
1
9
11

Figure 4



0.40
0.35
0.30
0.25
0.20
σ
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
δtp, sec
D=100, km
200
300
400
500
D=1000, km

Figure 5

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13. ABSTRACT

Study of the deviations of P and S travel times from the J-B tables at teleseismic distances has shown that there are regional differences in travel time. Both P and S are early in the central and eastern United States, late in the western United States. The differences have a range of about three seconds for P and eight seconds for S.

It can be deduced from the relation between the travel time residuals (1) that the change in shear velocity is approximately one and one-quarter times the change in P velocity, (2) that the observations imply a difference in Poisson's ratio between the two regions, and (3) that a model in which the shear modulus, μ, alone varies, the compressibility, k, remaining sensibly constant, fits the data best. It can be shown also that the differences between the P travel time residuals and the gravity anomalies in the central and western United States are not consistent with the Birch relation between velocity and density.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
P and S travel time anomalies						
regional differences in travel time						
shear velocity distribution						
Poisson's ratio						
upper mantle structure						
elastic constants in the upper mantle						
low velocity zone						
North American travel time anomalies						
temperature in the upper mantle						